Performance results of CERES instrument sensors aboard EOS Terra and Aqua spacecraft using tropical ocean measurements

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ABSTRACT

Clouds and the Earth's Radiant Energy System (CERES) instruments were designed to measure the reflected shortwave and emitted longwave radiances with three scanning thermistor bolometer sensors that measure broadband radiances in the shortwave (0.3 - 5.0 micrometers), total (0.3 - >100 micrometers) and 8 -12 micrometer water vapor window regions. Currently four of the CERES instruments (Flight Models1 through 4[FM1 - FM4]) are flying aboard EOS Terra and Aqua platforms with two instruments aboard each spacecraft. The Terra and Aqua spacecraft are at 705 km near polar, sun synchronous orbits with the equatorial crossing time of 10:30 AM and 1:30 PM.

One of the several validation studies for gauging the CERES sensors' performance utilizes the monitoring of tropical ocean longwave measurements for all sky condition. Previous studies on tropical ocean conducted by Earth Radiation Budget Satellite (ERBS) have shown that the mean longwave radiances remain very stable making it a suitable Earth target for validation. The difference in the tropical ocean daytime and nighttime longwave radiances measured by the two longwave measuring sensors on the same instrument are compared, to understand the total sensor's behavior in various spectral regions.

This paper focuses on the results from the tropical ocean measurement analysis called Tropical Mean (TM), calculated for all four CERES instruments aboard Terra and Aqua spacecraft. The TM results along with other validation and calibration studies have helped to detect variations that have occurred in the total sensors of FM2, FM3 and FM4 instruments aboard Terra and Aqua platforms. Further, the TM results has been used to help correct these variations in the ground processing system.

Keywords: CERES, TRMM, EOS, radiometry, calibration

1. INTRODUCTION

The Clouds and the Earth's radiant Energy System (CERES) experiment, part of NASA's Earth Observing System (EOS) investigations, is designed to measure the top of the atmosphere and surface radiation fluxes as a continuation of earth radiation budget measurements and to provide cloud property estimates that are consistent with radiative fluxes from surface to top of the atmosphere[1,2,3]. The CERES instruments are equipped to measure earth-reflected solar and earth-emitted longwave radiances, two components of earth radiation budget. The three components of the Earth Radiation Budget, the incoming solar, the outgoing earth-emitted longwave and earth-reflected shortwave radiances, were measured by the Earth Radiation Budget Experiment's (ERBE) scanning and non-scanning sensors during the 1980s and 1990s.

CERES sensors are similar in design to the Earth Radiation Budget Experiment's (ERBE) scanning bolometer sensors[4]. The CERES instrument consists of three detector units which measure the radiances in different spectral regions. First detector is a shortwave unit measuring earth-reflected solar radiances in the 0.3µm to 5.0 µm spectral region. The second unit is a total broadband radiometer which measures both earth-reflected and earth-emitted radiances in the 0.3µm to >100µm spectral region. The third unit known as the window sensor measures earth-emitted longwave radiances in the water vapor region of 8 - 12 µm. Currently there are four operational CERES instruments aboard the EOS Terra and Aqua spacecrafts, with two instruments on each platform. Both Terra and Aqua spacecrafts are in a sun synchronous orbit at 705 km altitude with the equatorial crossing time of 10:30 AM and 1:30 PM respectively.

The pre-launch measurement accuracy goals of the CERES sensors measurements are ± 0.5 $Wm^{-2}sr^{-1}$ for the filtered emitted longwave and ±0.8 $Wm^{-2}sr^{-1}$ for the filtered reflected shortwave radiances respectively. Inflight calibrations of the sensors with onboard sources and several validation studies using various Earth and atmospheric targets are conducted to achieve this goal. Since the longwave ocean measurements have been established as a relatively constant non-varying source, one of the Earth targets used for validation is the tropical ocean with its all cloud conditions. This paper presents the evaluation of Tropical Mean (TM) value using tropical ocean radiances measured by the CERES instruments. It also discusses the comparison of the TM value derived from Terra and Aqua instruments' measurements with respect to other ERBE and CERES instrument results, and how the TM results are used to understand the sensors' long-term performances in comparison with other studies.

2. CALIBRATION AND VALIDATION STUDIES

2.1. On-board Calibrations

Two different in-flight calibration systems were built into the CERES instrument package. These systems were used to define shifts or drifts in the sensor responses. The primary in-flight calibration system is called the internal calibration module (ICM). The ICM and the sensors carry the ground ITS-90 radiometric scale into orbit[5]. The ICM consists of 2.75-cm diameter, concentric grooved, anodized black aluminum blackbody sources for the total and window sensors, and an evacuated tungsten lamp source, known as the shortwave internal calibration source (SWICS), for the shortwave sensor. The mirror attenuator mosaic (MAM), a solar diffuser plate, is the second built-in system that is used to calibrate the shortwave and total sensors[6].

The ICM calibrations are conducted once a week for the shortwave sensor and three times a week for the total and window sensors. The solar calibrations using the MAM is conducted once every two weeks. Both the on-board calibration results are used to determine the shifts and long-term drifts appear in the gain coefficient of each CERES sensor.

2.2. Validation Tests

There are several tests that are being performed using Earth or atmospheric targets to validate the measured radiances from CERES sensors. Both single instrument and multi instrument validation studies can be conducted for CERES sensors aboard Terra and Aqua platforms. Single instrument tests include the comparison of longwave radiances derived from two sensors of the same instrument viewing the same target. Since there are two CERES instuments aboard each platform, results viewing the same geographical location from similar sensors of two instruments aboard the same spacecraft are used for multi instrument comparisons.

Tropical Mean analysis and three channel intercomparison are the two studies done using the single instrument sensors. Three channel intercomparison study uses the cold clouds as the atmospheric target for its comparison, whereas the tropical mean study utilises the tropical ocean as its earth target. Both studies use only vertical (nadir) measurements of the earth, to avoid the angular dependency on the sensor measurements. Since the CERES instrument does not have a true longwave sensor, the window sensor is trained with the night time total sensor radiance to act as a longwave channel. The second set of the long-wave radiance measurement is derived from the trained window sensor, for both these studies.

Intercomparison studies with sensors on two instruments was possible for the Terra and Aqua investigations. With two instruments aboard each platform, the sensors are viewing the same geographical locations in almost identical time. Comparisons are conducted on flux measurements with similar sensors of both instruments viewing the same scene. The resulting trends are categorised based on scenes and they highlight the variation appear between similar sensors of two instruments for different scenes.The results from the three validation studies all together give a clearer picture on the drifts occurring in any of the sensors on each instrument.

3. TROPICAL MEAN ANALYSIS

Tropical Mean (TM) value is the average of all vertical (nadir views) longwave radiances over the tropical ocean. Tropics is defined as a 40^0 latitude zone ($\pm 20^0$) centered at the equator. Since more than two-thirds of the tropical region is covered by ocean, the TM average use a very large sampling area. The increase in sampling area reduces the influence of the clouds in the calculation. Thus the results from the TM average is more stable than the one that is measured over a small geographical area.

Longwave radiances over land is not included in the TM statistic since they have strong diurnal variations which introduce more uncertainty in the TM value. The TM evaluation uses all sky condition that gives a less variable value than the all clear ocean or overcast condition in the tropics due to more uniform and higher sampling rate of the data. Choosing the all sky ocean in the study have eliminated any scene identification error and minimized the error from duirnal modeling. Eventhough the sampling rate was reduced to 2 samples per scan, the use of vertical radiances in TM evaluation eliminated the need to model longwave limb darkening effects.

TM study require a full uniform sample of the tropics. Uniform sampling is achieved by calculating the daily average of the latitude and longitude of each sample included in the study and requiring the mean latitude to be between $0.1^0 \pm 2.0^0$ and the mean longitude to be within $185^0 \pm 2.0^0$. The displacements from 0^0 and 180^0 result from the irregular ocean area over the tropics. The days with sampling within the range are accepted in the study. Another criteria for the day to be included in the study is to have the number of radiance samples to be at least 80 percent of the maximum sample day of the month.

For intercomparison between the satellites, the TM value is corrected to a common time. For this purpose, the daily averaged TM value is adjusted to noon, to correct for the duirnal change in the measurements. This eliminates the error caused by comparing the measurements from AM orbit to the one from the PM orbit. Both ascending and descending orbit data is included in the study. The TM value is calculated separately for day and night. The radiance measurements with the solar zenith angle less than 85^0 is considered for the daytime TM value and measurements with solar zenith angle over 95^0 is considered for nighttime value, to eliminate any problems from the light leakage near the terminator.

3.1. Intersatellite Tropical Mean Comparison

The TM value has been monitored for nearly two decades by several sensors such as Earth Radiation Budget Experiment (ERBE) scanners, Scanner for Radiation Budget(ScaRaB) and CERES scanners aboard TRMM, Terra and Aqua platforms. Study of 5 year ERBS scanner data that is used to calibrate the statistics of TM is detailed by Green *et. al.*[6]. The total sensor measurement at night is pure longwave radiance. The longwave(LW) radiance at nighttime show very small change over the years. Comparisons of the averaged nighttime TM value to study the variation between the different satellites was conducted.

The longwave radiance during day is determined by subtracting the shortwave radiance from the total sensor radiance. So any error in shortwave channel measurement can directly affect the daytime longwave TM value. For the CERES instrument, only one longwave radiance measurement is available at night since the second longwave sensor measures only the window region of 8 - 12 µm. The window sensor is trained to act as the second longwave sensor using the nighttime total sensor measurements. This is achieved by mapping a functional relationship between the longwave radiance from the total channel and the night time radiance from the window channel using a piecewise constant function of approximately 100 values. This approach is taken because the radiance from window sensor and the longwave radiance from total sensor are nonlinear. Thus two daytime TM values are derived for each CERES instrument; one from the trained window sensor and the second one from total and shortwave measurements.

3.2. TM Day-Night Difference Comparison

The difference between the day and night TM values is derived to study the inconsistencies occurring in the CERES sensors. Two sets of day-night difference (DN) values are derived for each instrument; one from the trained window sensor and the second one from the total and shortwave sensors. The difference between the day and night time TMs can be established very accurately with the window channel since the difference is insensitive to any calibration error and is not affected by shortwave radiation. This insensitivity is not true for the DN value derived from total and shortwave sensor measurements. Comparing the two DN values for the same instrument will surface any errors caused by total and/or shortwave sensor variation. The average DN value based on the longwave (window) sensor from all instrument is calculated which should be very reliable and represents the historical record of the DN statistic. The DN value derived from total and shortwave sensor of individual instrument is compared to the averaged DN value, to see the variation with the historic record.

3.3. TM Difference in DN Value

The third application of TM is used to test the consistency between the three channels of each CERES instrument. This is accomplished by calculating the difference between the DN based on the total and shortwave sensors and the DN based on the longwave (window) sensor. The DN from the longwave (window) channel removes the field variance from the DN based on the total and shortwave channels. A time history on this value will show the sensor drift between the three sensors. Calibration studies which evaluate each sensor’s response independently can show whether the response change if any, is occurring in shortwave or total sensor. The variation in the difference of DN value along with the calibration results of the total sensor, is indicative of whether the response change is occurring in the shortwave or longwave region of the total sensor.

4. TROPICAL MEAN RESULTS

The CERES Flight models 1 and 2 (FM1 & FM2) instruments aboard Terra spacecraft has been operating successfully for the past four years. The Aqua spacecraft carries the CERES Flight models 3 and 4 (FM3 & FM4) instruments, which has been operational since May 2002. The TM values are computed daily and the monthly averages are calculated for the day-night difference comparison.

4.1. Intersatellite TM Comparison Results

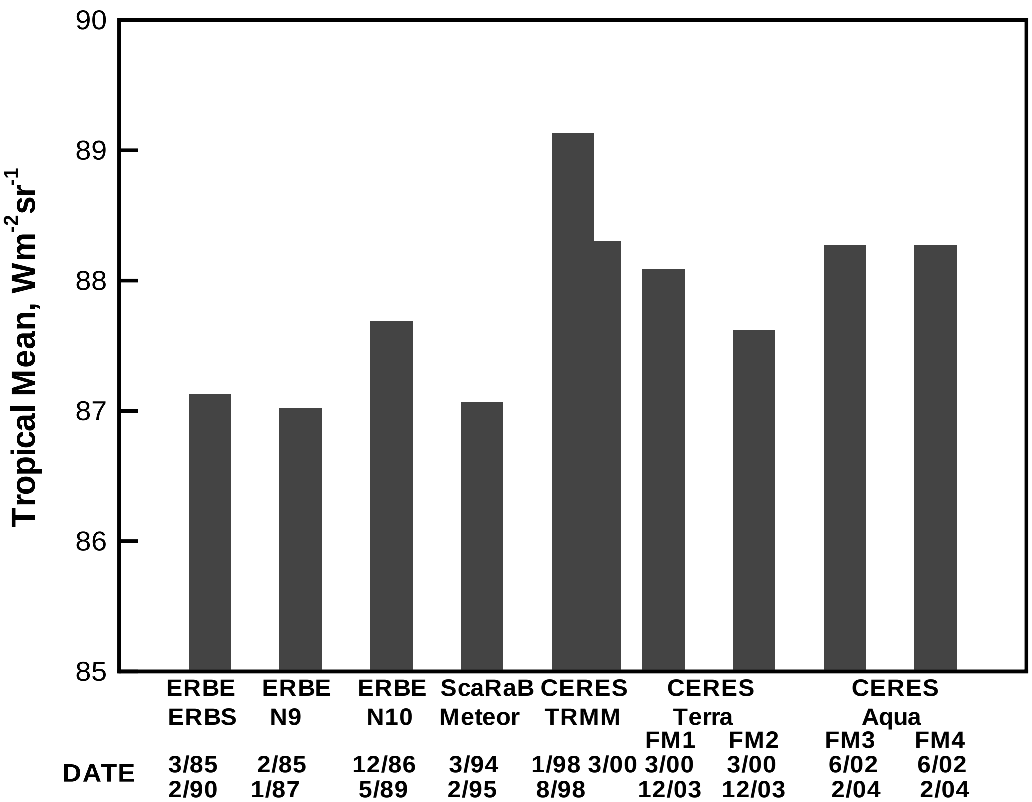

Fig. 1. Nighttime Tropical Mean (TM) longwave radiances for ERBE and CERES instrument sensors

The night time TM value is averaged for the entire period of its operation for each of the CERES instrument. The night time longwave radiance derived from total sensor is used for the comparison. Figure 1 shows the averaged TM value for all CERES instruments along with the ERBE instruments and ScaRaB instrument results. The 5 year average TM value derived for the period March 1985 to February 1990, from ERBS instrument is 87.13 $Wm^{-2}sr^{-1}$. The average values for the FM1 and FM2 instruments from the Edition-2 data are 88.09 $Wm^{-2}sr^{-1}$ and 87.62 $Wm^{-2}sr^{-1}$ respectively. The TM value is 88.27 $Wm^{-2}sr^{-1}$ for both Aqua instruments FM3 and FM4, for the period July 2002 to February 2004. All four CERES insruments are showing a higher value than the ERBS standard value. Since both Terra and Aqua instruments are in sun synchrounous polar orbits, the number of samples used in the daily averages are consistent throughout the month and more than 75 percent of the days in a month was included in the monthly averages. Thus we were able to obtain a fair distribution of the sampling for the Terra and Aqua instruments. The daily averages from each instrument were adjusted to noon (midnight) orbit for intercomparison. Since the equatorial crossing time does not vary for the Terra and Aqua spacecraft, the duirnal model cannot be developed for these instruments. The duirnal model developed from the ERBS data is used to correct the TM averages to the noon orbit.

The CERES instruments' daytime TM values derived from both longwave sensors are also compared with the ERBS daytime values. Figure 2 shows the results of the daytime TM comparison of CERES instruments with ERBS results. The day TM from window sensor is less variable between the CERES instruments, compared to the value derived from total and shortwave sensors. The average of day TM from trained window sensor is 88.99 $\pm$0.57 $Wm^{-2}sr^{-1}$, whereas the average day TM from total and shortwave sensors is 88.56 $\pm$0.69 $Wm^{-2}sr^{-1}$. The day TM from the trained window sensor is higher than the corresponding day TM from total and shortwave sensor in all CERES instruments, unlike the ERBS results. All the ERBE instruments and ScaRaB instrument showed that the results from the longwave sensor is lower than the day TM derived from total and shortwave sensor. The behaviour in the CERES instruments may be due to the fact that second longwave measurement is deriveds from trained window sensor, instead of a true longwave sensor as in ERBE instruments. The day as well as night TM averages for Aqua instruments are showing higher values than that of the Terra instruments from both longwave sensors. The TRMM instrument results for the period of Jan - Aug. 1998 show a higher than normal average for both sensors. This is attributed to the El-nino effect during the beginning of 1998. Due to the malfunctioning of one of the voltage converters on the CERES instrument aboard TRMM, the instrument was turned off after August 1998. It was subsequently turned on for the intercomparison with Terra instruments in March 2000, and we were able to obtain only one month of data from the TRMM CERES instrument.

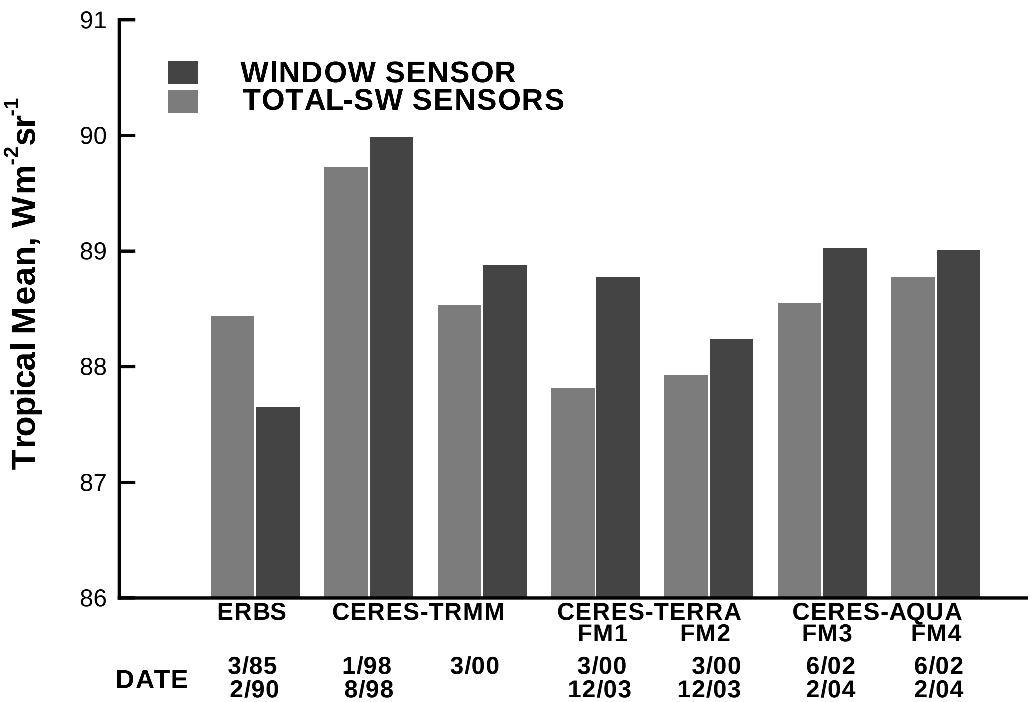

Fig. 2. Daytime TM values from the two longwave sensors for ERBS and CERES instruments

4.2. Day-Night Difference (DN) Comparison Results

Since there are two day time longwave TM values, two day night differences were calculated for the CERES instruments. Figure 3 shows the DN values for all CERES instruments derived from both sensors in comparison with the ERBS results. The average day-night difference (DN) based on trained window sensor is better suited for the intercomparison since it is more reliable. The average of DN from the trained window sensor for all the CERES instruments is 0.68 $\pm$0.08 $Wm^{-2}sr^{-1}$. The DN from window sensor is also showing a higher value for Aqua instruments, when compared to the Terra ones. The average DN for the Aqua instruments is 0.74 $Wm^{-2}sr^{-1}$, and for Terra instruments is 0.65 $Wm^{-2}sr^{-1}$.

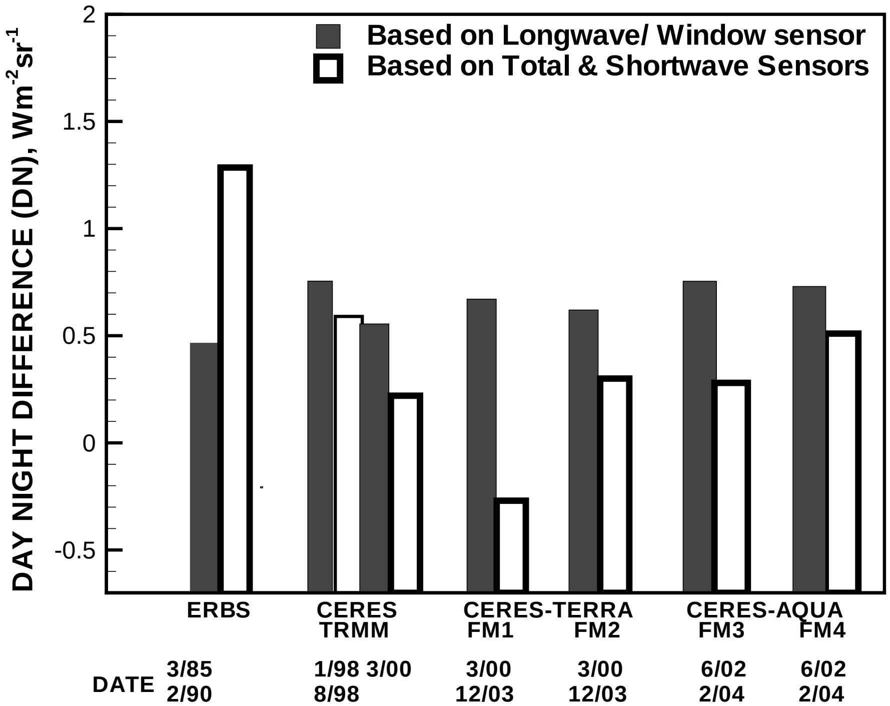

Fig. 3. Day -Night Difference (DN) averages derived from total & shortwave sensors and longwave(window) sensor for ERBS and CERES instruments

The DN value derived from the total and shortwave sensors show much more variability. The average DN for all the CERES instruments from the total and shortwave sensors is 0.27 $\pm$ 0.3 Wm-2sr-1. The FM1 DN value is much lower compared to the results from other CERES instruments. In addition, the FM1 day TM average is lower than night TM average, resulting in a negative DN value, whereas all the other instruments are showing a positive DN value. The DN derived from trained window sensor is higher in all CERES instruments to the corresponding average DN from the total and shortwave sensor. This may be attributed to a leak of the window sensor in the shortwave spectral region, which in turn will result in higher measurement for the daytime longwave value.

4.3. Comparison Results of Difference in DN Value

The consistency between the three channels of each CERES instrument is tested by comparing the DN values derived from the longwave sensors. The difference between the DN values is studied for uncovering any trends seen in any of the sensors. Analysis of the Edition-1 data have shown that the difference of DN value was showing a rise in all CERES instruments. The risewas most predominant in the FM2 instrument. This can occur either by under estimation of the shortwave radiation by the shortwave sensor or the over estimation of the daytime measurement by the total sensor resulting in a higher longwave measurement. The DN from the window sensor is relatively stable since measurements from only one sensor is involved in calculating this value. The noise in the monthly DN values is removed by calculating the difference between the DN values. The results from the direct comparison of CERES sensors on same spacecraft viewing the same geolocation is used to verify the trens in shortwave and total sensors. The shortwave sensors are not showing any drop in any of the CERES instruments, but the daytime longwave value is showing an upward trend.

Figures 4 and 5 show the DN difference value of Edition-1 and Edition-2 data in Terra and Aqua instruments. Independent on-board calibration results have shown that the total sensor gains are increasing in the Terra instruments[8], and the gains for the shortwave sensors in Aqua instruments are decreasing. In addition to the drifts in the gain coefficients of these sensors, the difference in DN value comparisons have shown that the total sensor is showing an upward trend in the shortwave spectral

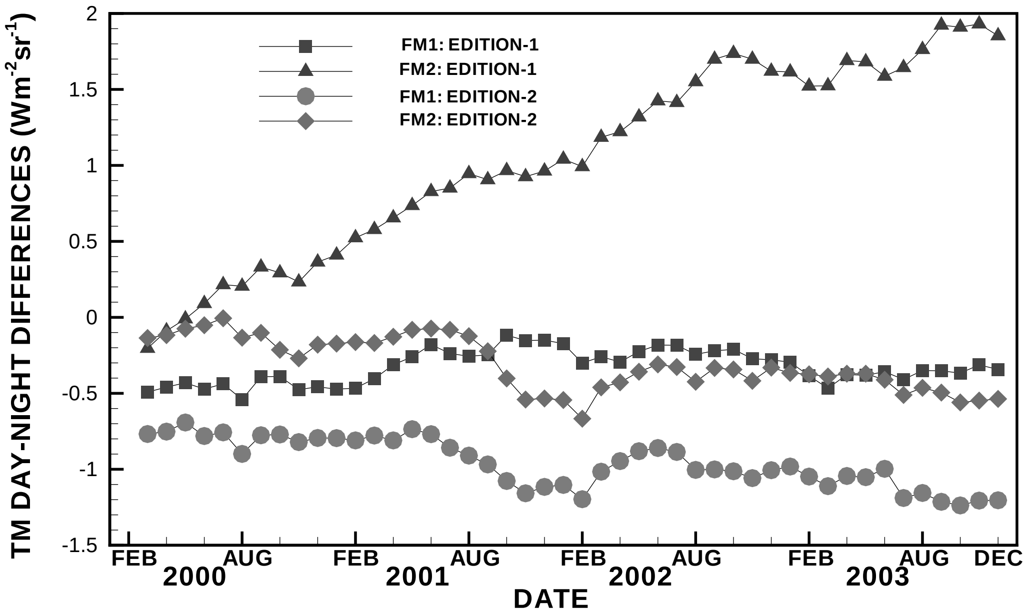

Fig. 4. Difference in Day-Night difference (DN) values for Editions 1 & 2 Terra CERES instrument measurements

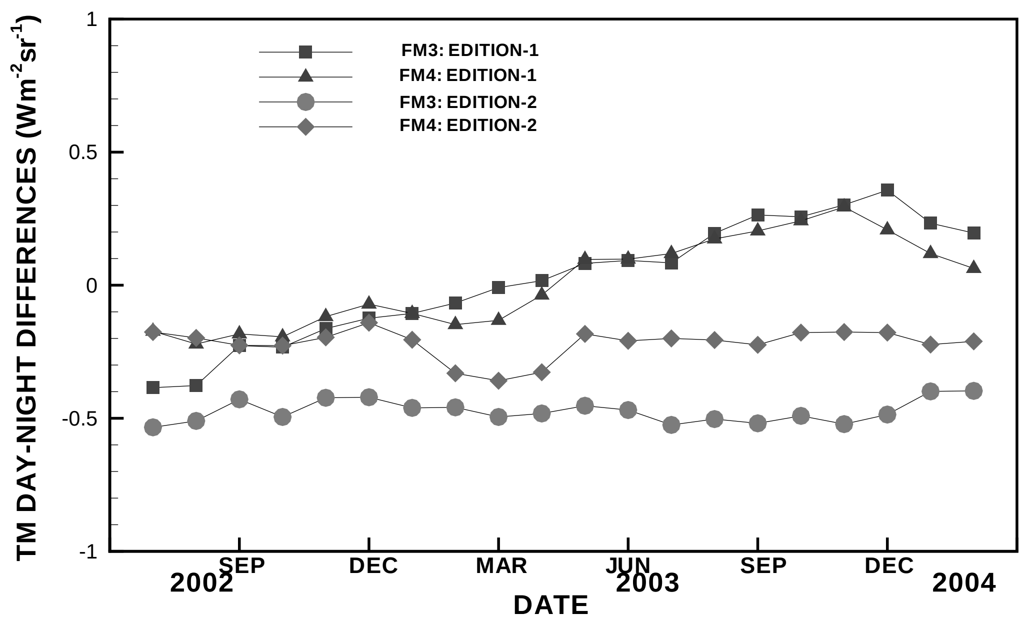

Fig. 5. Difference in Day-Night difference (DN) values for Editions 1 & 2 Aqua CERES instrument measurements

region during the initial period of all CERES instruments. This is evident in the Edition-1 results shown in Figures 4 and 5. Other validation studies such as the three channel intercomparison of CERES sensors have also shown the rise in the shortwave region of the total sensor [9]. The gain and spectral coefficients values for the appropriate sensor in each CERES instrument are adjusted to correct for the drift in the radiance measurements. The results from Edition-2 data in Figures 4 and 5 show the difference in the DN values from the corrected radiance measurements.

5. CONCLUSION

The TM analysis, one of the tools used for validating CERES measurements, has enabled us to test the consistency of sensors on all of the CERES instruments. The night time TM comparisons between various instruments was instrumental in understanding the CERES instrument behaviour with respect to ERBE instruments. The two instruments aboard the same spacecraft have made it possible to conduct comparison studies with similar sensors on both instruments as well as various sensors on individual instrument. All the studies have asserted that a rise is occurring in the daytime measurements of the total sensors in FM2, FM3 and FM4 instruments. This is attributed to the behaviour of total sensors in shortwave spectral region. Corrections based on these studies have stabilised the day time longwave measurements in Edition-2 data products.

6. ACKNOWLEDGMENTS

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7. REFERENCES

1. B. A. Wielicki, B. R. Barkstrom, E.F. Harrison, R. B. Lee III, G. L. Smith, and J. E. Cooper, “Cloud’s and the Earth’s Radiant Energy System (CERES): An Earth Observing System Experiment”, *Bulletin of American Meteorological Society*, **77**, pp 853-868, 1996

2. B. A. Wielicki, B. R. Barkstrom, B. A. Baum, T. P. Charlock, R. N. Green, D. P. Kratz, R. B. Lee III, p. Minnis, G. L. Smith, T. Wong, D. F. Young, R. D. Cess, J. A. Coakley, Jr., D. H. Crommelynck, L. Donner, R. Kandel, M. D. King, A. J. Miller, V. Ramanathan, D. A. Randall, L. L. Stowe, and R. M. Welch, “Clouds and the Earth’s Radiant Energy System (CERES): Algorithm Overview,” *IEEE Transactions on Geoscience and Remote Sensing*, Vol **36**, No. 4, 1127 - 1141, July 1998.

3. B. R. Barkstrom, “Earth radiation budget measurements: Pre - ERBE, ERBE, and CERES”, *Proc. of SPIE*, **1299**, 52-60, 1990.

4. R. B. Lee III, B. R. Barkstrom, G. L. Smith, J. E. Cooper, L. P. Kopia, R. S. Lawrence, S. Thomas, D. K. Pandey, D. H. Crommelynck, “The Clouds and the Earth’s Radiant Energy System (CERES) Sensors and Preflight Calibration Plans”, *Journal of Atmospheric and Oceanic Technology*, Vol **13**, No. 2, 300-313, April 1996.

5. S. Thomas, R. B. Lee III, K. J. Priestley, B. R. Barkstrom J. Paden, D. K. Pandey, R. S. Wilson, A. Al-Hajjah, “Early trends on the Clouds and the Earth’s Radiant Energy System (CERES) instruments’ performances using in-flight calibration sources, for Earth Science Enterprise (ESE) Terra mission”, *Proc. SPIE*, v. **4030**, 2000.

6. R. S. Wilson, R. B. Lee III, B. R. Barkstrom, H. Bitting, J. Paden, D. K. Pandey, K. J. Priestley, G. L. Smith, S. Thomas, K. L. Thornhill, “On-Orbit solar calibrations using the TRMM Clouds and the Earth’s Radiant Energy System (CERES) in-flight calibration system”, *Optical Sci.*, *Eng. & Instrum.*, *Proc. SPIE*, v. **3439**, July, 1998.

7. R. N. Green, K. J. Priestley, “The Tropical Mean as a validation parameter for satellite radiances”, J*ournal of Atmospheric and Oceanic Technology*, Sub. May 2001

8. Thomas S., K. J. Priestley, R. B. Lee III, P. L. Spence, R. S. Wilson, A. Al-Hajjah, J. Paden, and D.K. Pandey, "Performance studies of CERES sensors on Earth Science Enterprise (ESE) Terra mission using on-board calibrations and other validation methods", Proceedings of the 9th International Symposium on Remote Sensing, Crete, Greece, September 2002

9. P. L. Spence, K. J. Priestley, E. A.Kizer, S. Thomas, D. L. Cooper, D. L. Walikainen, “Correction of drifts in the measurements of the Clouds and the Earth’s Radiant Energy System (CERES) scanning thermistor bolometer instruments on the Terra and Aqua satellites”, *Proc. SPIE*, v. **5542** (this issue), 2004